Coherent structure and turbulent mixing in the hurricane boundary layer observed by unmanned aircraft

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With many thanks to the COYOTE team!
What is Coyote UAS?
An experimental, small, semi-autonomous, “uncrewed” aircraft, deployed from a “crewed” aircraft.
Deployment of Coyote UAS
Atmospheric Measurements

For more details, see Cione et al. 2016 (*Earth and Space Science*)

Wind determined using onboard devices (e.g., pitostatic pressure): up to 10 Hz

New for 2017: infrared (IR) sensor for sea-surface temperature

Table 2. Specifications for the Meteorological Sensors Aboard the Coyote

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Manufacturer/Model</th>
<th>Range</th>
<th>Tolerance</th>
<th>Response Time (s)</th>
<th>Sampling Rate (Hz)</th>
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<tr>
<td>Pressure</td>
<td>HoneywellSCCP15ASMT</td>
<td>5–1070 mb</td>
<td>±0.5 mb</td>
<td>&lt;1.0</td>
<td>3</td>
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<tr>
<td>Temperature</td>
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<td>−80–60°C</td>
<td>±0.3°C</td>
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<tr>
<td>Humidity</td>
<td>E + EHC103M2</td>
<td>0–100%</td>
<td>±5%</td>
<td>&lt;5.0 at 25°C</td>
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Atmospheric Measurements

For more details, see Cione et al. 2016 (Earth and Space Science)

Wind determined using onboard devices (e.g., pitostatic pressure): up to 10 Hz

Note: all data in this talk are preliminary

Wind speed data provided by NOAA/ARL/ATDD (Ron Dobosy, Ed Dumas, Michael Buban, Temple Lee)

New for 2017: infrared (IR) sensor for sea-surface temperature

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P3 follows the SUAS after releasing it. A total of 9 eyewall penetrations were completed for each P3 flights. P3 was circling in the eyewall when the SUAS was operated.
SUAS (Coyote) flight track and wind speed
Friction velocity ($u_*$)

$$|\tau| = \left[ \frac{u'w'^2 + v'w'^2}{u^*} \right]^{1/2} = u_*$$

Andreas et al. (2012, JAS)
Two New Capabilities ...

2. Large-Eddy Simulation (LES): High-resolution model simulations

Details:

Wind speed (m s\(^{-1}\)) at \(z = 100\)m

\[\Delta x = \Delta y = 31 \text{ m} \]
\[\Delta z = 15.5 \text{ m}\]

over 80 km x 80 km inner fine mesh (entire domain is 3000 km x 3000 km)

5-min animation, image every 2 s

Richter et al. (2016, JAS)
Worsnop et al. (2017, GRL)
Stern and Bryan (2018, MWR, subm.)
Gust Factor

Color shading:
Maximum Gust Factor, defined as
\[ GF = \frac{\text{max 3-s avg.}}{\text{10-min avg.}} \]

Black contours:
max. 3-s-avg wind gust

Worsnop et al. (2017, GRL)
Using Coyote UAS Observations to Evaluate Large-Eddy Simulations (and Vice Versa)

1. Using Coyote data to evaluate simulations

2. Using simulations to interpret Coyote data
Coyote data: Flight 3 (altitude)

Level flight segments
<U> = 55.0 m/s
\sigma = 3.7 m/s
TI = \sigma/<U> = 0.067
z \approx 400 m
Spectra of along-wind (u) and vertical (w) velocity

The spectra of u and w at frequency > 0.5 Hz generally follow the -5/3 slope (black dashed line), indicating the wind retrieval is reasonably good.
Cospectrum of $u$ and $w$

Strong downward transfer of momentum flux is caused by sub-km scale eddies.
Strong downward transfer of momentum flux caused by sub-km scale eddies is seen near the top of the boundary layer ($z=\sim1$km).
Wavelength: Larger-scale structures ~ 1500 to 2000 m
Smaller-scale structures ~ 300 to 700 m

Along-roll velocity Perturbations: +/- 7 m s$^{-1}$ typical
up to +/- “10s of” m s$^{-1}$ small-scale

Orientation: Typically along-mean wind, ±30 deg

Prevalence: Roll-scale structures common, (35% to 70%)
Streak-scale structures: Most likely usually present
Turbulence kinetic energy:

\[
\text{TKE} = \frac{1}{2} \left( \langle u' u' \rangle + \langle v' v' \rangle + \langle w' w' \rangle \right)
\]

\[
= \frac{4.7 \text{ m}^2 \text{ s}^{-2}}{}
\]
Turbulence Kinetic Energy: \[ TKE = \langle u'u' \rangle + \langle v'v' \rangle + \langle w'w' \rangle \] / 2

Colors indicate different Coyote flights.
Turbulence Kinetic Energy:  \[ \text{TKE} = \frac{\langle u' u' \rangle + \langle v' v' \rangle + \langle w' w' \rangle}{2} \]

As \( z \) increases, TKE decreases.
Horizontal wind speed (m s\(^{-1}\)) from Simple* LES setup

(*small domain, specified wind at top of boundary layer)

CM1:
\[ \Delta x = \Delta y = 10 \text{ m}, \]
\[ \Delta z = 5 \text{ m} \]

Bryan et al. (2017, BLM)
Horizontal wind speed (m s\(^{-1}\)) from three simulations

CM1:
\[ \Delta x = \Delta y = 20 \text{ m}, \]
\[ \Delta z = 10 \text{ m} \]
Normalized Turbulence Kinetic Energy: \[
\frac{TKE}{U^2} = \frac{\left(\langle u' \rangle^2 + \langle v' \rangle^2 + \langle w' \rangle^2 \right)/2}{U^2}
\]

**CM1:**
\[
\Delta x = \Delta y = 20 \text{ m},
\Delta z = 10 \text{ m}
\]
Normalized Turbulence Kinetic Energy: \[ \frac{\text{TKE}}{U^2} = \frac{\left(\langle u' u' \rangle + \langle v' v' \rangle + \langle w' w' \rangle\right)/2}{U^2} \]

**CM1:**

\[ \Delta x = \Delta y = 20 \text{ m}, \]

\[ \Delta z = 10 \text{ m} \]
Using Coyote UAS Observations to Evaluate Large-Eddy Simulations (and Vice Versa)

1. Using Coyote data to evaluate LES
   • Such comparisons are quite rare

2. Using simulations to interpret Coyote data
Back to the Complex* Large-Eddy Simulation
(*larger domain, simulate entire hurricane inner core)

Details:

Wind speed (m s\(^{-1}\)) at z = 100m

\[ \Delta x = \Delta y = 31 \text{ m} \]
\[ \Delta z = 15.5 \text{ m} \]
Average in time and along azimuths: tangential velocity ($v$, m s$^{-1}$)

CM1:
$\Delta x = \Delta y = 31$ m,
$\Delta z = 15.5$ m
Average in time and along azimuths: vertical turbulent flux of $v$ (m$^2$ s$^{-2}$)

$\langle v'w' \rangle$ (m$^2$ s$^{-2}$, shaded); $\langle v \rangle$ (m s$^{-1}$, contours)

CM1:
$\Delta x = \Delta y = 31$ m,
$\Delta z = 15.5$ m
Average in time and along azimuths: radial velocity ($u$, m s$^{-1}$)

CM1:
$\Delta x = \Delta y = 31$ m,
$\Delta z = 15.5$ m
CM1:
\[ \Delta x = \Delta y = 31 \text{ m}, \]
\[ \Delta z = 15.5 \text{ m} \]

Average in time and along azimuths: vertical turbulent flux of \( u \) \( (m^2 \text{ s}^{-2}) \)
Summary

• Rare turbulence data in hurricanes
  • (observed and simulated)

• Turbulence metrics from Coyote and LES are comparable
  • Patterns are similar [e.g. TKE (z)]
  • Magnitude [TKE, T.I.] roughly a factor of 2 different
    • (very preliminary)

• Future work:
  • Level Coyote flight legs for \( z < 100 \) m (for \( u^* \), \( C_d \), \( C_k \) measurements)
  • Simulations: calibrate/tune LES based on Coyote data

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